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13. ABSTRACT *(Maximum 200 words)*

The problem of breakup of masses of liquid agents moving at supersonic speeds at high altitudes is important for missile defense and other Army problems. Traditionally such studies are carried out in expensive field, sled and reverse ballistic tests. To reduce costs and improve controllability, we have built a shock tube with Mach 8 capability to study breakup; it works well and we are taking some data: see http://www.aem.umn.edu/research/Aerodynamic_Breakup. This proposal is to do systematic comparisons of breakup on a wide range of simulants using our shock tube and to do theoretical studies to interpret the data. Another goal is to embed breakup studies in as yet underdeveloped branch of mechanics which I call the "breaking strength of materials". The theory of cavitation, the tensile strength of liquids and the fracture of amorphous solids may be framed in a unified manner in which the breaking strength is compared to stresses along the principle axes of stress. The formation of cracks or bubbles is probably controlled by the mobility of the material which can be different even in the same material, say, in molten and frozen glass. We seek to make a connection between the aerodynamic breakup of liquids, and topics related to cavitation; condensation, diffusion and outgassing of dissolved gas.

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Studies of aerodynamic breakup, cavitation and rupture of fluids
DA/DAAG 55-98-1-3014

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The project on aerodynamic dissemination is of interest to several agencies of the Army and funding for a continuation of our shock tube studies and new initiatives for correlating data are being discussed by BMDO.

Significant progress has been made on this project over the grant period. Two theoretical –experimental studies (in the references) were prepared on Rayleigh-Taylor instability of drops in high speed airflow (high Weber numbers) and one study of Kelvin Helmholtz instability which may play a role in breakup.

A paper on the cavitation of liquids in a journal bearing based on the maximum tensile stress rather than pressure was published. We showed that the conventional criterion based on the pressure underestimates the risks to cavitation; the stress coming from motion plays a significant role. We have done studies of drop breakup at very high altitudes, very low pressures. We learned that outgassing of absorbed water was an important factor in the breakup at high altitudes. We carried out studies and created models for outgassing in the "so called" foamy oils.

1. Technical Objectives and Motivation

The goal of research on aerodynamic dissemination is to determine the fraction, placement and drop size distribution of agents exposed to a high-speed air stream at high altitudes.

The problem is to understand the dissemination of agents which are exposed to a high Mach number air stream, between, say, M=3 and M=8 at high altitudes. It is known that a liquid mass is reduced to a droplet cloud in hundreds of microseconds. It is believes that considerable amounts of vapor or mist are produced, but that the mechanisms of breakup, the distribution of drop sizes, the volume fractions of mist and vapor and the precise effects of thickening agents on the droplet distribution and breakup mechanism are not known. The unknowns are inputs for computer codes designed to predict how the droplet clouds are disseminated, where they will drift and the condition and size of the droplets that ultimately reach the ground.

This is a very difficult problem because there is such a great difference between the breakup of organic liquids (solvent) and thickened liquids (solvent plus polymers). Organic liquids shatter into small drops and mist at high Mach numbers, but at the highest Mach numbers tested so far (slightly supersonic), viscoelastic fluids are pulled into threads but don't shatter. From this research, (possibly the first) data for thickened agents up to Mach 8 in our shock tube will be obtained. It is vital to see if and how these threads persist in the severe conditions behind a strong shock.

The problem is significant because without more precise knowledge of the mechanisms and consequences of breakup and the condition of the droplet cloud immediately after breakup, the dissemination of agents is unpredictable and uncontrollable.

It turns out that the shock tube is the only way to look at high altitude breakup at low cost. The low pressure environment does change the dynamics and we are studying this.

2. Technical Approach

We are gathering results from the shock tube studies and from an outgassing jar bell. In a controlled way. The results are interpreted by physical reasoning and math analysis in a traditional way.

3. Significant Accomplishments

The shock tube experiments described in the references probe high Weber number breakup in regimes which could not be accessed before. Many new results some of which are reported in the references, have been and are being attained. The role of Rayleigh-Taylor instability in breakup has been demonstrated. We are now able to assess the effects of thickeners. We did experiments on TEP, DEM, and TBP neat and thickened. A final report of these tests appears in "Shock Tube Experiments on Aerodynamic Breakup of Thickened Liquids" by Joseph, Beavers, Brendan, Eichman and Hannah performed for Army Labs under Battelle contract 135905 which can be obtained from them.

4. Cooperation with Army Laboratories

We were collaborating with BMDO (Col. Sylvia Ferry) through separate $100,000/ year sub-contract with Battelle (Carl Alexander) to fund shock tube studies. We are now talking to Dan Williard who represents Walt Hollis at the Pentagon.

5. Main Publications Relevant to this work

D.D. Joseph, *Cavitation and the state of stress in a flowing liquid*, J.of Fluid Mech. 366, 367-378 (1998)

D.D. Joseph, J. Belanger, G.S. Beavers, *Breakup of a liquid drop suddenly exposed to a high speed airstream*, Int. J. Multiphase Flow, in press (1999)

D.D. Joseph, G.S. Beavers, and T. Funada, *Rayleigh-Taylor Instability of Viscoelastic Drops at High Weber numbers*, submitted for publication (1999)

A. Pereia, G. McGrath, D.D. Joseph, 2001. Flow and stress induced cavitation in a journal bearing with axial throughput, *J. Tribology*, **123**, 742-754.

D.D. Joseph, G.S. Beavers, T. Funada, 2001. Rayleigh-Taylor instability of viscoelastic drops at high Weber numbers, *J. Fluid Mech.*, (2002) **453**, 109-132.

T. Funada, D.D. Joseph, 2001. Viscous potential flow analysis of Kelvin-Helmholtz instability in a channel, *J. Fluid Mech.*, **445**, 263-283.

D.D. Joseph, A. Kamp, R. Bai, 2001. Modeling Foamy Oil Flow in Porous Media, *Int. J. Multiphase Flow*, In progress.

D.D. Joseph, A.M. Kamp, R. Bai, 2002. Foamy Oil Flow in Porous Media, *Confinement and Remediation of Environmental Hazards and Resource Recovery, IMA Volumes in Mathematics and its Applications, Vol #*, J. Chadam, A. Cunningham, R.E. Ewing, P. Ortoleva, M. Wheeler, Springer-Verlag, To appear.

6. Awards and Honors

The P.I. of this ARO-sponsored research, Daniel D. Joseph, was named the Timoshenko medallist of the ASME for 1995 and he received the Thomas Baron Fluid-Particle Systems Award of AIChE for 1996. He received the Illinois Institute of Technology Professional Achievement Award from the University of Chicago. He gave the L.S. Kovazny Distinguished Lecture at the University of Houston in 1999. He won the 1999 Fluid Dynamics Prize from the American Physical Society. There is a week long symposium to honor the contributions of Dan Joseph to fluid mechanics June 23-28, 2002 at the 2002 IUTAM meeting in Blacksburg, VA.

7. Students and post-docs supported by ARO grants

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